# ATMOSPHERIC TURBULENCE WITHIN AND ABOVE A DOUGLAS-FIR STAND. PART II: EDDY FLUXES OF SENSIBLE HEAT AND WATER VAPOUR

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**Abstract.** This is the second paper describing a study of the turbulence regimes and exchange processes within and above an extensive Douglas-fir stand. The experiment was conducted on Vancouver Island during a two-week rainless period in July and August 1990. Two eddy correlation units were operated in the daytime to measure the fluxes of sensible heat and water vapour and other turbulence statistics at various heights within and above the stand. Net radiation was measured above the overstory using a stationary net radiometer and beneath the overstory using a tram system. Supplementary measurements included soil heat flux, humidity above and beneath the overstory, profiles of wind speed and air temperature, and the spatial variation of sensible heat flux near the forest floor.

The sum of sensible and latent heat fluxes above the stand accounted for, on average, 83% of the available energy flux. On some days, energy budget closure was far better than on others. The average value of the Bowen ratio was 2.1 above the stand and 1.4 beneath the overstory. The mid-morning value of the canopy resistance was 150–450 s/m during the experiment and mid-day value of the Omega factor was about 0.20. The daytime mean canopy resistance showed a strong dependence on the mean saturation deficit during the two-week experimental period.

The sum of sensible and latent heat fluxes beneath the overstory accounted for 74% of the available energy flux beneath the overstory. One of the reasons for this energy imbalance was that the small number of soil heat flux plates and the short pathway of the radiometer tram system was unable to account for the large horizontal heterogeneity in the available energy flux beneath the overstory. On the other hand, good agreement was obtained among the measurements of sensible heat flux made near the forest floor at four positions 15 m apart.

There was a constant flux layer in the trunk space, a large flux divergence in the canopy layer, and a constant flux layer above the stand. Counter-gradient flux of sensible heat constantly occurred at the base of the canopy.

The transfer of sensible heat and water vapour was dominated by intermittent cool downdraft and warm updraft events and dry downdraft and moist updraft events, respectively, at all levels. For sensible heat flux, the ratio of the contribution of cool downdrafts to that of warm updrafts was greater than one in the canopy layer and less than one above the stand and near the forest floor.

## 1. Introduction

An experiment to study the exchange processes within and above a coniferous forest of Douglas-fir trees was conducted on Vancouver Island during a two-week rainless period in July and August 1990. This paper is the second of two reporting the results of the data analysis of the experiment. The first paper (Lee and Black, 1993, hereafter referred to as I) described the statistics of the velocity field. This paper reports the results of the analysis of eddy fluxes of sensible heat and water vapour within and above this stand. As part of the analysis, energy budget closure above the stand and beneath the overstory is examined. The big leaf model is

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used to calculate the canopy resistance and Omega factor of the stand, a measure of the coupling between the vegetation and the atmosphere, for the purpose of describing the response of the stand to the changes in atmospheric variables. The implications of measured flux profiles, namely, the relationships between the flux and source distribution and the phenomenon of counter-gradient flux are addressed. Finally, the technique of quadrant-hole analysis is used to identify the kinds of motion which dominate the exchange processes.

## 2. Experimental Methods

### 2.1. Site description

The experiment was conducted in late July and early August 1990. The most recent rainfall event prior to the experiment occurred on 6 July. The weather remained mostly clear during the experimental period. The average water content of the root zone (0–60 cm) was 0.19 on 27 July, 0.13 on 2 August and 0.11 kg/kg on 17 August on a dry soil basis. The soil is a gravelly sandy loam very similar to that described by Nnyamah and Black (1977). During the late stage of the experiment, there was water stress of the trees as indicated by some needle yellowing.

### 2.2. Instrumentation and initial data treatment

Primary instrumentation included two 3-dimensional eddy correlation units described in I. In the early stage of the experiment, three 1-dimensional sonic anemometer/thermocouple units (Campbell Scientific Inc.) were operated at 2 m above the forest floor and located in the upwind direction of the main instrument tower. The main tower and the three 1-dimensional units were positioned approximately along a line with 15 m separation from each other. The signals from the three units were sampled at 10 Hz by a data logger (Campbell Scientific Inc., 21X with extended software II), which gave on-line calculations of sensible heat flux at 5-min intervals and averaged for every 30-min period. The measurements with the 1-dimensional units were only used for evaluating the spatial variation in sensible heat flux from the forest floor. For all other analyses, the measurements with the 3-dimensional units were used.

Net radiation flux above the stand was measured with a net radiometer (Swissteco Instruments, Oberriet, Switzerland, Model S-1) at a height of 24.0 m. Net radiation flux near the forest floor was measured at a height of 1.3 m ($z/h = 0.08$) with two net radiometers of the same type: one mounted on a tram and moving back and forth at a speed of 1.49 m/min along a 15.6 m pathway (Black *et al.*, 1991) and the other at a height of 1.3 m at a fixed position. Only data collected with the tram system were used in the analysis of energy budget beneath the overstory. Soil heat flux was measured with two pairs of soil heat flux plates (one pair, Middleton Instruments, Australia, Model F; one pair, home-made following the design of Fuchs and Tanner (1968)) placed at a depth of 3 cm and two nickel wire integrating thermometers to correct for the change in heat storage in the surface soil layer.

Relative humidity was measured at heights of 24.0 and 1.5 m with two hygrometers (Physical-Chemical Corp., New York, NY, Model PRC). Both sensors were calibrated against an Assmann psychrometer (Casella Ltd., London, England) in the field. Air temperature and wind speed were measured with fine wire thermocouples (chromel-constantan, 25 $\mu$m in diameter) and sensitive cup anemometers (C. W. Thornthwaite Associates, Centerton, NJ, Model 901-LED), respectively, at heights of 0.9, 2.0, 4.6, 7.0, 10.0, 12.7, 16.7 and 23.0 m.

Soil water content was measured gravimetrically once a week. Soil water content of the root zone (0–60 cm) was measured at a 5 cm increment at two locations. Soil water content of the surface layer (0–3 cm) was measured at four locations and was used to determine the volumetric heat capacity of this layer for the calculations of soil heat flux.

Turbulence statistics were calculated over 30-min intervals. A two-way coordinate rotation was applied to the statistics measured at the heights of 16.7 m and 23.0 m, following the procedure of Tanner and Thurtell (1969), and a one-way coordinate rotation applied to the statistics measured within the stand, following the procedure of Baldocchi and Hutchison (1987). Corrections were made to the measurements of water vapour flux made with the krypton hygrometers to account for the effect of oxygen (Massman *et al.*, 1990) and the effect of the air density due to the simultaneous transfer of heat and water vapour (Webb *et al.*, 1980).

### 2.3. Theoretical Considerations

Assuming horizontal homogeneity and neglecting the energy used in photosynthesis, the energy budget of the forest stand can be expressed as

$$R_n - S - G = H + \lambda E \,, \tag{1}$$

where $R_n$ is the net radiation flux above the stand, $G$ is the soil heat flux, $H$ is the sensible heat flux above the stand, $\lambda E$ is the latent heat flux above the stand, and $S$ is the rate of heat storage per unit ground area in the layer between the 0 and 23.0 m heights, all of which have units of W/m$^2$. Ideally the available energy flux, $R_n - S - G$, should be balanced by the sum of the eddy fluxes, $H + \lambda E$.

The rate of heat storage, $S$ was separated into the following four components:

$$S = S_s + S_l + S_{nb} + S_t \,,$$

where $S_s$ is the rate of sensible heat storage in the air, $S_l$ is the rate of latent heat storage in the air, $S_{nb}$ is the rate of heat storage in the needles and branches, and $S_t$ is the rate of heat storage in the tree trunks. The first three components can be expressed as

$$S_s = \int_0^{23m} \rho c_p \frac{\partial T_a}{\partial t} \mathrm{d}z \,, \tag{2}$$

$$S_l = \int_0^{23m} \lambda \frac{\partial \rho_v}{\partial t} \, dz \, , \tag{3}$$

$$S_{nb} = \int_0^{23m} m c_{nb} \frac{\partial T_{nb}}{\partial t} \, dz \, , \tag{4}$$

where $\partial T_a/\partial t$, $\partial \rho_v/\partial t$, and $\partial T_{nb}/\partial t$ are the time rates of change in air temperature, water vapour density and temperature of the needles and branches; $\rho$ is the air density, $c_p$ is the specific heat of air at constant pressure, $\lambda$ is the latent heat of vaporization of water, $m$ is the mass of the needles and branches per unit volume of air, and $c_{nb}$ is the specific heat of the needles and branches. Using appropriate values for $\rho$, $c_p$ and $\lambda$, (2) and (3) reduce to

$$S_s = 14.2 \Delta \bar{T}_a \, ,$$

$$S_l = 31.2 \Delta \bar{\rho}_v \, ,$$

where $\Delta \bar{T}_a$ (°C) and $\Delta \bar{\rho}_v$ (g/m$^3$) are the changes over a 30-min interval in air temperature and water vapour density averaged over the layer between 0 and 23.0 m. $\Delta \bar{T}_a$ was calculated from the measurements of air temperature made at the eight heights, and $\Delta \bar{\rho}_a$ was approximated by the measurement of water vapour density made at the height of 24.0 m. Using the mass of needles and branches estimated from the samples collected for determining the leaf area distribution and a value of 2647 J/(kg °C) for $c_{nb}$ based on the specific heat of dry wood (Cohen *et al.*, 1985) and corrected for the measured water content of the needles and branches, (4) reduces to

$$S_{nb} = 4.3 \Delta \bar{T}_{nb}$$

where $\Delta \bar{T}_{nb}$ (°C) is the change over a 30-min interval in the average temperature of the needles and branches, estimated to a good approximation from the change in air temperature averaged over the heights of 7.0, 10.0, 12.7 and 16.7 m. The rate of heat storage in the trunk ($S_t$) was estimated, using a method similar to that used by Denmead and Bradley (1985), from a solution obtained by Herrington (1969) for radial heat flow in a semi-infinite slab with a periodic surface temperature. Using the values for bulk density, specific heat and thermal diffusivity of Douglas-fir wood (Cohen *et al.*, 1985) and the average surface area of a trunk, and approximating the trunk surface temperature by air temperature in the stand (assumed to vary sinusoidally), $S_t$ is expressed as

$$S_t = 3.5 A_{Ta} \cos(\omega t - \phi + \pi/4) \, , \tag{5}$$

where $A_{T_a}$ (°C) and $\phi$ are the amplitude and phase angle of the diurnal course of air temperature in the stand, respectively, $\omega$ is the diurnal angular frequency which equals $\pi/12$ (rad/h), and $t$ is the time of the day.

The bulk canopy resistance ($r_c$) was obtained from the Penman–Monteith equation, i.e., the big-leaf model (Monteith 1965)

$$r_c = \frac{\rho c_p D}{\gamma \lambda E} + r_a[(\beta s/\gamma) - 1], \tag{6}$$

where $D$ is the saturation deficit measured at 24.0 m, $\gamma$ is psychrometric constant, $s$ is the slope of the saturation vapour pressure curve at air temperature, $r_a$ is the aerodynamic resistance to water vapour and sensible heat diffusion between the reference height (23.0 m in the present study) and their effective source heights (assumed to be the same), and $\beta$ is the Bowen ratio calculated from the measured eddy fluxes. The aerodynamic resistance, $r_a$ was approximated by the aerodynamic resistance to momentum transfer ($r_m$) without stability and excess resistance corrections

$$r_a = r_m = u/u_*^2,$$

where $u$ is the mean wind speed at the reference height, and $u_*$ is the friction velocity. This simplification will not introduce much error in $r_c$ since of the two terms on the RHS of (6), the first term is dominant.

## 3. Results and Discussion

### 3.1. Eddy Fluxes above the Stand

#### 3.1.1. *Energy Budget Closure*

Figure 1 shows the sum of the eddy fluxes ($H + \lambda E$) measured at $z/h = 1.38$ plotted against the available energy flux ($R_n - S - G$). On average, $H + \lambda E$ accounted for 83% of $R_n - S - G$. The correlation coefficient was 0.85 for a total of 118 thirty-min runs. The following sources of error contributed to the energy imbalance and the scatter in Figure 1. First, neglect in (1) of the solar energy used in photosynthesis would result in overestimating the available energy flux by 1–4% (Verma *et al.*, 1986; Stewart and Thom, 1973). Second, estimating the heat storage component with the method described above was subject to uncertainties. McCaughey (1985) showed that in a dry, mixed forest, the temporal change in biomass temperature lagged behind that in air temperature within the stand. Part of the effect of the time lag was incorporated into (5). But (5) was only a first-order approximation, since the temporal course of air temperature was not perfectly sinusoidal. Third, the heat flux into the soil was characterized by large horizontal uncertainties due to the high horizontal heterogeneity of the solar irradiance on the forest floor. Consequently, two pairs of heat flux plates were insufficient to provide a good spatial average of $G$.

The choice of averaging time interval is important for eddy correlation measurements. McMillen (1988) suggests a time constant of 200 s for the running mean removal for the on-line computation of fluxes. Shuttleworth *et al.* (1984) found that an increase of the time constant from 18.75 to 31.25 min resulted in a 2% increase in the sensible and latent heat fluxes measured over an Amazonian forest.

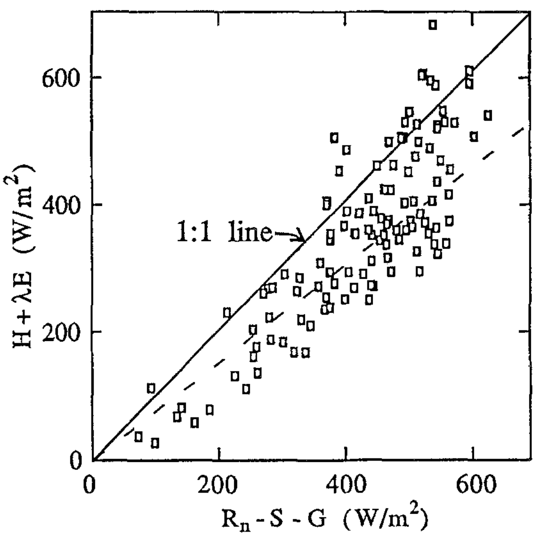


Fig. 1. Comparison of the sum of the eddy flux densities ($H + \lambda E$) measured at $z/h = 1.38$ and the available energy flux density ($R_n - S - G$) for the Douglas-fir stand at Browns River during the entire experimental period in 1990. The dashed line represents the linear regression forced through zero with a slope of 0.83.

Using the Reynolds averaging procedure, the fluxes and other statistics of this study were first calculated over 5-min intervals and averaged for each 30-min period. A large flux loss occurred, with $H + \lambda E$ being only 75% of $R_n - G - S$. This was due to the effect of low frequency cut-off and indicated the importance of eddies with periods exceeding 5 min. The atmosphere was moderately to strongly unstable in the daytime during the experimental period (I). According to an estimate of McBean (1972) for the unstable surface layer, the loss of covariance resulting from the low frequency cut-off at 0.0033 Hz, a frequency corresponding to the period of 5 min, is on the order of 10%. By changing the averaging time interval to 30 min, the energy budget closure was increased by 8% to 83%. Further increase in the averaging time interval, however, had little effect on the computation of fluxes. The averaging interval of 30 min therefore appears to be a good choice.

Table I lists the daytime average components of the energy budget for the stand for the nine experimental days. The sky was clear except on 26 July and 1 August, when partly cloudy conditions occurred. The average values of $R_n$, $H$ and $\lambda E$ during the measurement periods on the nine days were 449, 231 and 115 W/m$^2$, respectively. On some days, energy budget closure was much better than on others. The values of the ratio, $(H + \lambda E)/(R_n - S - G)$ ranged from 0.67 (31 July) to 0.96 (20 July).

Figure 2 shows the daytime variation of the energy budget components on 1 August and on 28 July. On 1 August, it was partly cloudy. The fluctuations in $R_n$

TABLE I

Average values of the energy budget components, $R_n$, $G$, $S$, $H$ and $\lambda E$ (W/m$^2$) during the indicated periods for the Douglas-fir stand at Browns River. Also shown are the values of the ratio, $(H + \lambda E)/(R_n - S - G)$, and the daytime Bowen ratio, $\beta$

| Date<br>Hour (PST) | 19 July<br>11:30–18:00 | 20 July<br>9:30–16:00 | 26 July<br>9:00–16:30 | 27 July<br>12:00–17:30 | 28 July<br>8:30–16:00 |
|---|---|---|---|---|---|
| $R_n$ | 462 | 533 | 444 | 460 | 512 |
| $G$ | 13 | 21 | 13 | 8 | 21 |
| $S$ | 7 | 23 | 20 | 15 | 36 |
| $H$ | 183 | 286 | 230 | 241 | 264 |
| $\lambda E$ | 142 | 184 | 113 | 111 | 113 |
| $\frac{H + \lambda E}{R_n - S - G}$ | 0.76 | 0.96 | 0.83 | 0.81 | 0.83 |
| $\beta$ | 1.3 | 1.6 | 2.0 | 2.2 | 2.3 |
| Date<br>Hour (PST) | 29 July<br>12:00–19:00 | 30 July<br>9:00–16:30 | 31 July<br>12:30–17:30 | 1 August<br>9:00–17:00 | Mean |
| $R_n$ | 376 | 469 | 319 | 469 | 449 |
| $G$ | 12 | 11 | 7 | 12 | 13 |
| $S$ | 6 | 22 | 3 | 18 | 17 |
| $H$ | 171 | 271 | 139 | 292 | 231 |
| $\lambda E$ | 88 | 110 | 69 | 107 | 115 |
| $\frac{H + \lambda E}{R_n - S - G}$ | 0.73 | 0.87 | 0.67 | 0.91 | 0.83 |
| $\beta$ | 1.9 | 2.5 | 2.0 | 2.7 | 2.1 |

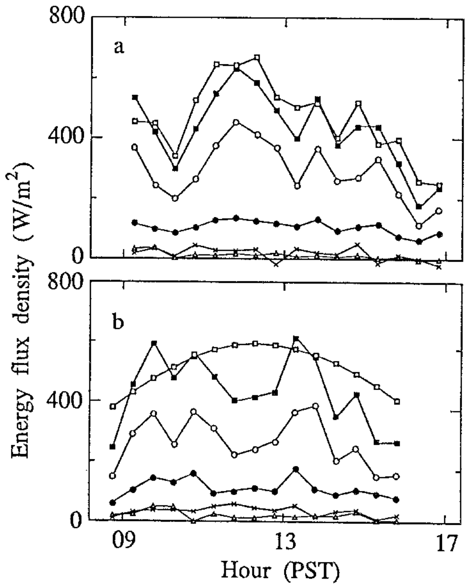


Fig. 2. Energy budget closure as shown by the comparison of values of $R_n$ (□) and $H + \lambda E + S + G$ (■) for the Douglas-fir stand at Browns River on (a) a partly cloudy day (1 August) and (b) a clear day (28 July 1990). Also shown are the variations of $H$ (○), $\lambda E$ (●), $G$ (△) and $S$ (×).

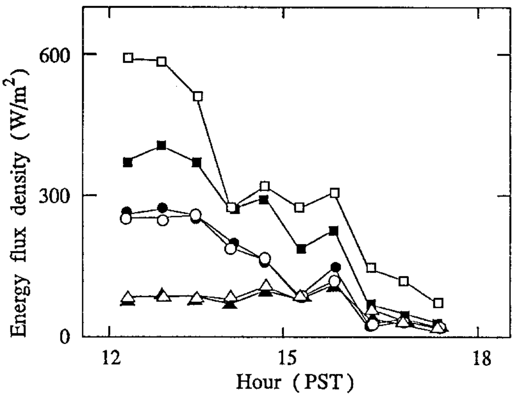


Fig. 3. Comparison of eddy fluxes measured at $z/h = 1.38$ ($H$ (●) and $\lambda E$ (▲)) and at $z/h = 1.00$ ($H$ (○) and $\lambda E$ (△)) for the Douglas-fir stand at Browns River on 31 July, 1990. Also shown are $R_n$ (□) above the stand and $H + \lambda E + G + S$ (■) for $z/h = 1.38$.

were closely followed by the fluctuations in $H$ and $\lambda E$, and good closure was obtained. The three main energy budget components on this day peaked at around 12:00 PST, the peak values of $R_n$, $H$ and $\lambda E$ being 669, 456 and 135 W/m$^2$, respectively.

It was perfectly clear on 28 July, as indicated by the smoothness of the $R_n$ record. But large fluctuations were observed in $H$ and $\lambda E$. There was a significant energy imbalance around noon. During the period between 11:30 and 13:00 PST, the average available energy flux ($R_n - S - G$) was 524 W/m$^2$, while sensible and latent heat fluxes were only 244 and 107 W/m$^2$, respectively, the ratio, $(H + \lambda E)/(R_n - S - G)$ being 0.66.

The large imbalance did not appear to be related to wind direction, since the daytime wind blew very constantly from the NE–ENE as a result of land–sea/upslope–downslope circulations, and cannot be fully accounted for by the sources of error discussed above. Furthermore, it was very unlikely that the imbalance was caused by instrument malfunction. This is demonstrated by the good agreement in the measurements made by the two eddy correlation units. On 31 July and 1 August, the lower eddy correlation unit was operated at $z/h = 1.00$. In I, it was shown that on these two days the covariance of the vertical velocity and air temperature and the covariance of the vertical velocity and water vapour density measured at $z/h = 1.00$ agreed very well with those measured at $z/h = 1.38$. Figure 3 shows the daytime variation of the fluxes measured at these two heights on 31 July. The measurements at the two heights were almost identical. But, as on 28 July, there was a large energy imbalance around noon.

The energy imbalance is believed to be the result of a possible non-zero average vertical velocity (in the present study, the velocity component perpendicular to the slope surface) observed at a single point. As stated by Webb *et al.* (1980), the important underlying requirement for measuring vertical scalar fluxes by the eddy correlation technique is that there is no net mass flux of dry air from the surface. This requirement may not be satisfied over non-flat terrain. For example, it can be shown that, by applying the potential flow model to flow over a two-dimensional object (Fox and McDonald, 1985), the streamline at a certain distance away from the surface will be slightly misaligned with the slope. The non-zero average vertical velocity might also be the result of the stationary cell-like structure of the flow under convective conditions in the planetary boundary layer (Thurtell, G. W. 1991, personal communication). In some areas there are ascending movements, which are compensated by the descending movements in the surrounding areas. The vertical velocity at a single point even though averaged over a certain time period, is likely different from zero. Because of the non-zero average vertical velocity, the eddy correlation measurement will tend to underestimate the vertical fluxes of sensible and latent heat. For instance, a mean vertical velocity of 1 cm/s, with water vapour density of 5 g/m$^3$, the typical value during the experimental period, would account for a water vapour flux of 0.05 g/(m$^2$ s) or a latent heat flux of about 120 W/m$^2$ from the surface.

### 3.1.2. *Canopy Resistance and the Omega Factor*

The daytime Bowen ratio increased with time during the 9-day experimental period from 1.3 to 2.7 as the soil dried (Table I). This is not surprising considering the steep water retention curve for this coarse soil (Nnyamah and Black, 1977) and the shallow root zone.

The canopy resistance of Douglas-fir stands has a strong dependence on the soil water potential and saturation deficit of the air ($D$). It increases as soil water potential decreases and as $D$ increases (Tan and Black, 1976). Figure 4 shows the daytime variation in $r_c$ and $D$ on 19 and 20 July. The mid-morning value of $r_c$ varied between 150 and 450 s/m during the experiment, and generally tended to increase with time in the late afternoon as $D$ increased. The magnitude and the time trend reported here agree with those obtained with the energy balance/Bowen ratio technique for slightly younger Douglas-fir stands under water stress (Price and Black, 1990, 1991; Tan and Black, 1976).

Figure 5 shows the courses of daytime mean canopy resistance and saturation deficit during the experimental period. The daytime mean canopy resistance $r_c$ was obtained by weighting the half-hourly values of $r_c$ by $D$ as follows (Tan and Black, 1976)

$$\overline{r_c} = \bar{D} \Big/ \frac{1}{n} \sum_{i=1}^{n} (D_i / r_{ci}) ,$$

where $D_i$ and $r_{ci}$ are the half-hourly values of $D$ and $r_c$, and $\bar{D}$ is the arithmetic average of the daytime $D$. At very similar values of $\bar{D}$, $\bar{r}_c$ was higher on 29 July than on 19 and 20 July, a result of the steady decrease in soil water content during

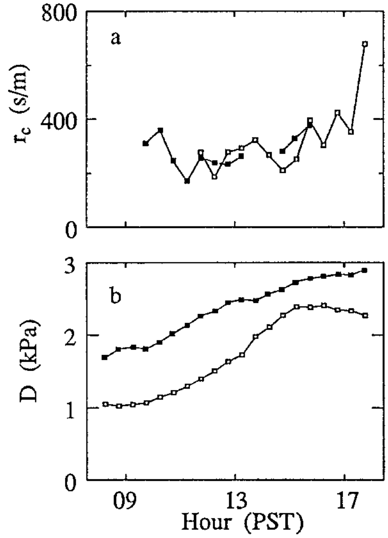


Fig. 4. Daytime variation of (a) canopy resistance $r_c$, and (b) saturation deficit $D$ for the Douglas-fir stand at Browns River on 19 July (□) and 20 July, 1990 (■).

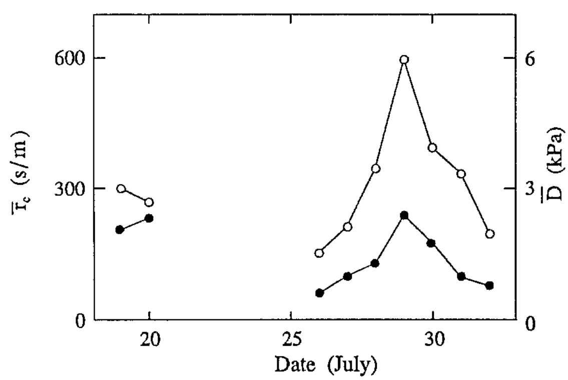


Fig. 5. Courses of daytime mean canopy resistance $\bar{r}_c$ (○) and mean saturation deficit $\bar{D}$ (●) for the Douglas-fir stand at Browns River in 1990.

the experimental period. During the period between 26 July and 1 August, $\overline{r_c}$ was well correlated with $\bar{D}$.

McNaughton and Jarvis (1983) and Jarvis (1985) introduced the concept of coupling between vegetation communities and the atmosphere in terms of the dimensionless decoupling factor

$$\Omega = (s/\gamma + 1)/(s/\gamma + 1 + r_c/r_a) ,$$

where $\Omega$ has values between zero and one. They suggested $\Omega$ values of about 0.1

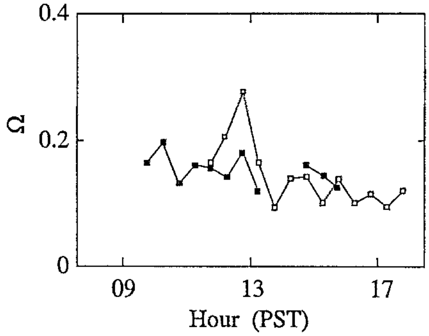


Fig. 6. Daytime variation of Omega factor (Ω) for the Douglas-fir stand at Browns River on 19 July (□) and 20 July, 1990 (■).

TABLE II

Daytime average values of the energy budget components, $R_n$, $G$, $H$ and $\lambda E$ (W/m$^2$) beneath the overstory of the Douglas-fir stand at Browns River in July 1990. Also listed are the ratio, $(H + \lambda E)/(R_n - G)$, the daytime Bowen ratio, $\beta$, and the relative height $(z/h)$ of the measurement of $H$ and $\lambda E$

| Date<br>Hour(PST) | 19<br>12:00–18:00 | 20<br>9:30–16:30 | 26<br>9:00–16:30 | 27<br>11:00–16:30 | 28<br>8:30–16:00 |
|---|---|---|---|---|---|
| $z/h$ | 0.12 | 0.12 | 0.12 | 0.42 | 0.42 |
| $R_n$ | 97 | 157 | 106 | 113 | 137 |
| $G$ | 11 | 21 | 13 | 10 | 21 |
| $H$ | 33 | 47 | 52 | 48 | 47 |
| $\lambda E$ | 29 | 48 | 29 | 26 | 34 |
| $\frac{H + \lambda E}{R_n - G}$ | 0.73 | 0.69 | 0.88 | 0.72 | 0.69 |
| $\beta$ | 1.1 | 1.0 | 1.8 | 1.9 | 1.4 |

to 0.2 for forests (strong coupling) and about 0.8 to 0.9 for grasslands (weak coupling). Based on their analyses, transpiration from trees is expected to follow closely the saturation deficit and to be controlled by the canopy resistance. Figure 6 shows the daytime variation of the Omega factor on 19 and 20 July. The mid-day value of Ω was around 0.2, a value close to those suggested by McNaughton and Jarvis (1983) and Jarvis (1985). Similar results were obtained on the remaining days.

## 3.2. Eddy fluxes beneath the overstory

### 3.2.1. *Energy Budget Closure*

Table II lists the daytime average value of the energy budget components beneath the overstory of the stand. The rate of heat storage in the air and trunks was very small, and was neglected. On 19, 20 and 26 July, eddy correlation measurements were made at $z/h = 0.12$. Later, on 27 and 28 July, measurements were made at $z/h = 0.42$, the approximate height of the canopy base. Divergence of the eddy fluxes between these two heights was very small (Figure 10). The value of the ratio of the daytime total eddy flux of sensible and latent heat $(H + \lambda E)$ to the available energy flux $(R_n - G)$ ranged from 0.66 to 0.88, with an average value of 0.74. The large heterogeneities in $R_n$ and $G$ (see below) may be one of the reasons for the energy imbalance. But overall closure was satisfactory, bearing in mind that each component of the energy budget was of small magnitude.

Although it was a small component in the energy budget of the whole stand, $G$ was significant in the energy budget beneath the overstory. As above the stand, $H$ was the largest output component of the energy budget, but was not as dominant. The value of $\beta$ was close to one on the first two days (19 and 20 July) and greater than one on the later three days (26, 27 and 28 July), with a mean value of 1.4. The increase of $\beta$ with time was a result of soil drying and was consistent with the trend of the Bowen ratio above the stand.

### 3.2.2. *Temporal and Horizontal Variations in the Energy Budget Components*

Figure 7 presents the daytime variation of the energy budget components beneath the overstory and the net radiation flux above the stand on 20 and 26 July. Skies were clear on 20 July and partly cloudy on 26 July. The midday values of $H$ and $\lambda E$ were about 60 and 70 W/m$^2$ on 20 July and 90 and 40 W/m$^2$ on 26 July, respectively. The trends of $H$ and $\lambda E$ were similar to the trend of net radiation above the stand rather than $R_n$ measured near the forest floor.

Considerable fluctuations occurred in $R_n$ measured near the forest floor, even under clear sky conditions (Figure 7b). This suggests that the pathway of the tram system was not long enough to obtain a good spatially averaged value of $R_n$. Large fluctuations also occurred in $G$. To obtain more reliable measurements of $R_n$ and $G$ in this stand, the length of the tram pathway and the number of heat flux plates would have to be increased.

The optimal length of the pathway of the tram depends on crown closure. The same tram system has given satisfactory measurements of shortwave and longwave irradiances in an unthinned Douglas-fir stand of similar age (Black *et al.*, 1991). The pathway length/tree spacing ratio in that study was about 6.3. Using this ratio as a rule of thumb, the pathway length should have been increased to 26 m for a reliable measurement of $R_n$ in the present study.

Figure 8 compares the half-hourly values of kinematic sensible heat flux $\overline{w'T'}$ near the forest floor measured at four positions with the three 1-dimensional sonic anemometer/thermocouple units and the 3-dimensional sonic anemometer/thermometer unit. Figure 9 shows the daytime variation of the kinematic sensible heat flux measured with the four units on 26 July, 1990. Good agreement was obtained among the measurements of the three 1-dimensional units: much of the scatter fell in the range of $\pm 15\%$. The flux measured with the 3-dimensional unit was slightly lower than that measured with the 1-dimensional units. The results indicate

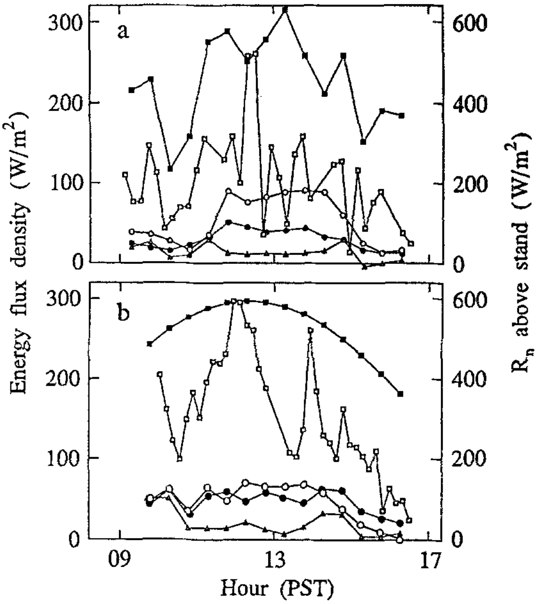


Fig. 7. Variation of the energy budget components, $R_n$ (□), $H$ (○), $\lambda E$ (●) and $G$ (△) beneath the overstory of the Douglas-fir stand at Browns River on (a) a partly cloudy day (26 July) and (b) a clear day (20 July, 1990). Also shown is the variation of the net radiation flux density above the stand (■).

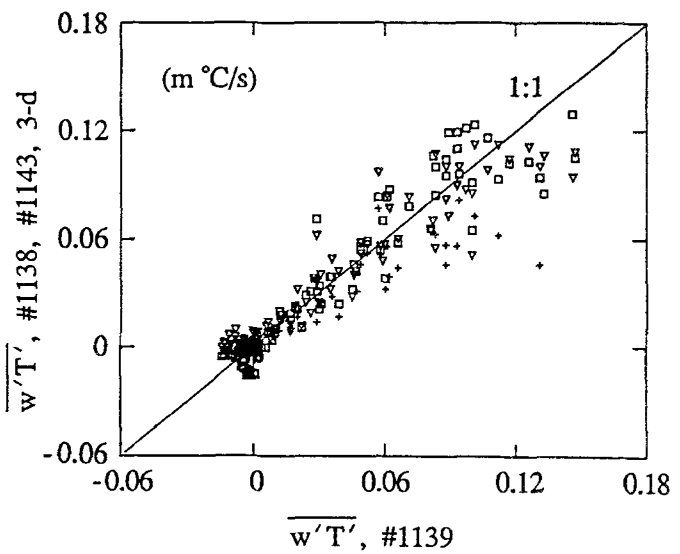


Fig. 8. Comparison of the kinematic sensible heat flux $\overline{w'T'}$ at 2 m ($z/h = 0.12$) above the forest floor of the Douglas-fir stand at Browns River measured at four positions in July 1990 with three 1-dimensional sonic anemometer/thermocouple units (#1138, #1139, #1143) and one 3-dimensional sonic anemometer/thermometer unit (3-d): (□), #1138; (▽), #1143; (+), 3-d.

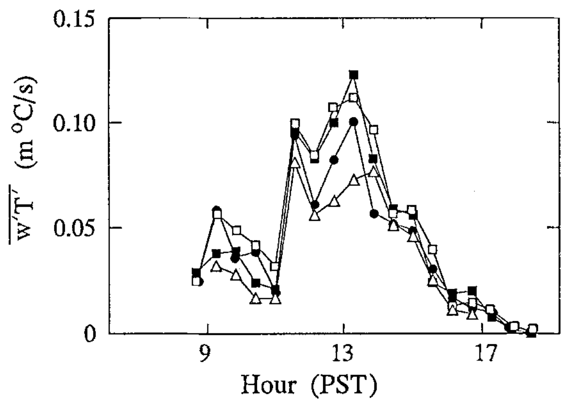


Fig. 9. Daytime variation of the kinematic sensible heat flux $\overline{w'T'}$ at 2 m ($z/h$ = 0.12) above the forest floor of the Douglas-fir stand at Browns River on 26 July, 1990 measured with three 1-dimensional sonic anemometer/thermocouple units (#1138 (■), #1139 (●), #1143 (□)) and one 3-dimensional sonic anemometer/thermometer unit (△).

that the eddy correlation measurement made at 2 m provided a good spatial average of the sensible heat flux from the forest floor and the understory in this pruned and thinned stand.

### 3.3. Profiles of Eddy Fluxes

Figure 10 shows the sensible heat and water vapour fluxes at various heights in the stand as fractions of the corresponding fluxes at $z/h = 1.38$. Two constant flux layers occurred, one above the tree tops and the other in the trunk space. Within the canopy layer, the fluxes increased approximately linearly with height. This pattern of vertical profiles, also observed by Denmead and Bradley (1985) in a pine forest, reflects the density distributions of the sensible heat and water vapour sources. The stand in the present study had two distinct sources: the forest floor (including a little short understory vegetation) and the canopy, separated by the trunk space of approximately 6 m in height. While flux divergences in the trunk space were very small because of the negligible source density in the trunk space, the non-zero source density of the foliage resulted in large flux divergences in the canopy layer. But the divergences were not proportional to the leaf area density. For example, based on Figure 10, of the total flux divergence of sensible heat in the canopy layer, 54% came from the layer between $z/h = 0.60$ and 1.00, which had 40% of the canopy leaf area (I), and 46% came from the layer below $z/h$ = 0.60, which had 60% of the canopy leaf area. In other words, for the same amount of leaf area, the source density of sensible heat was higher in the upper canopy than in the lower one. This might be a result of higher radiation absorption per unit leaf area in the upper canopy than in the lower one. Based on the finding for a Douglas-fir stand of similar structure that stomatal resistance varied little with

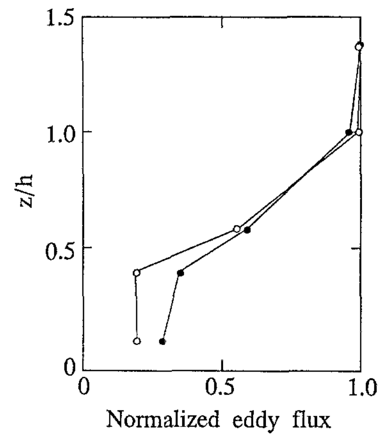


Fig. 10. Normalized profiles of daytime averaged sensible heat flux (○) and water vapour flux (●) in the Douglas-fir stand at Browns River in 1990. The average values of the standard error of the mean were 0.085 at $z/h = 0.60$ and 0.025 at all other heights.

height (Tan *et al.*, 1978), we believe that the stomatal effect on the source density distributions was minimal.

The profiles of sensible heat and water vapour fluxes were somewhat dissimilar in that the forest floor contributed less to the total sensible heat flux from the stand (19%) than to the total water vapour flux (26%). This may imply the inequality of the effective source heights for sensible heat and water vapour. By analogy to the centre-of-pressure theorem (Thom, 1971), the effective source height, $d$ can be expressed as

$$d = \frac{\int_0^h zS(z)\,\mathrm{d}z}{\int_0^h S(z)\,\mathrm{d}z + F_g}, \tag{7}$$

where $S(z)$ is the flux divergence or source density at height $z$ and $F_g$ is the flux from the forest floor. Physically, (7) defines the height of the zero-plane displacement. With the aid of the data in Figure 10, (7) gives an estimate of $d$ = 9.6 m or $d/h = 0.57$ for sensible heat and $d$ = 8.7 m or $d/h = 0.52$ for water vapour. The difference in $d/h$ between sensible heat and water vapour was small compared to the large uncertainties in the ratio $d/h$ for forests (Jarvis *et al.*, 1976), and seems to support the general use of a single $d$ for heat and water vapour (Thom, 1972).

Both sensible heat and water vapour fluxes within the stand were directed upward for the majority of the runs. The numbers of the runs with upward sensible heat flux (total numbers of runs in brackets) at $z/h = 0.12$, 0.42 and 0.60 were, in order, 40 (42), 27 (28) and 26 (29), and the corresponding figures for water vapour flux were 41 (42), 27 (28) and 29 (29). The runs with downward fluxes occurred during the quiescent periods in the late afternoon when the upslope wind was being replaced by the downslope wind, and the fluxes were very small. Daytime

TABLE III

Values of the covariances of the vertical velocity component and air temperature ($\overline{w'T'}$) and the vertical velocity component and water vapour density ($\overline{w'\rho_v'}$),, standard deviations of air temperature ($\sigma_T$), water vapour density ($\sigma_{\rho_v}$) and the vertical velocity component ($\sigma_w$) at the indicated heights for the five runs selected for quadrant-hole analysis of eddy fluxes of sensible heat and water vapour for the Douglas-fir stand at Browns River. The stability parameter $(z - d)/L$ was calculated from the measurements at $z/h = 1.38$

| Time interval PST | $z/h$ | $(z-d)/L$ | $\overline{w'T'}$ m °C/s | $\overline{w'\rho_v'}$ g/(m$^2$ s) | $\sigma_T$ °C | $\sigma_{\rho_v}$ g/m$^3$ | $\sigma_w$ m/s |
|---|---|---|---|---|---|---|---|
| 13:30–14:00 19 July | 0.12 | −0.26 | 0.055 | 0.008 | 0.66 | 0.32 | 0.19 |
| 12:00–12:30 27 July | 0.42 | −0.25 | 0.112 | 0.015 | 0.75 | 0.15 | 0.32 |
| 12:30–13:00 30 July | 0.60 | −0.35 | 0.117 | 0.006 | 0.76 | 0.16 | 0.33 |
| 13:30–14:00 1 Aug | 1.00 | −0.25 | 0.217 | 0.017 | 0.77 | 0.12 | 0.54 |
| 12:00–12:30 27 July | 1.38 | −0.25 | 0.335 | 0.033 | 0.78 | 0.17 | 0.75 |

air temperature characteristically exhibited a maximum near the ground ($z/h$ = 0.12) and an inversion in the layer between $z/h = 0.28$ and 0.60 (Lee, 1992). In other words, counter-gradient flow occurred as has been frequently observed in forests (Denmead and Bradley, 1985; Amiro, 1990; Leclerc, 1987). The existence of counter-gradient flow is due in part to the sporadic penetration of transporting eddies into the canopy and their large scales (Denmead and Bradley, 1985). In the context of a Lagrangian framework, it can be understood as a near-field effect of the canopy heat source (Raupach, 1987). The phenomenon of counter-gradient flow at these heights invalidates K-theory. However, K-theory appears to be able to give a reasonable prediction of fluxes near the forest floor (Lee, 1992).

### 3.4. Quadrant Representation of Eddy Fluxes

The technique of quadrant-hole analysis has been widely used to reveal the structure of turbulent transfer of momentum and scalars in vegetation canopies. In I, it was shown that a major proportion of momentum transfer near the top of the stand and in the canopy layer occurred during intense intermittent sweep/ejection events. It was also shown that the magnitude of interaction contributions to the momentum transfer was greater than that of sweep/ejection contributions at the canopy base ($z/h = 0.42$) and in the middle of the trunk space ($z/h = 0.12$), which was consistent with the negative values of Reynolds stress at these heights.

Table III lists the set of the selected runs (same as used in I) for performing the quadrant-hole analysis of sensible heat and water vapour fluxes. The results are summarized in Tables IV and V, where $H'$ is the hole size above which half of the flux occurs

TABLE IV

Summary of the results of quadrant-hold analysis for sensible heat flux of the five-runs in Table III

| $z/h$ | 0.12 | 0.42 | 0.60 | 1.00 | 1.38 |
|---|---|---|---|---|---|
| $H'$ | 5.7 | 5.2 | 4.6 | 3.5 | 3.7 |
| $\sum_{i=1}^{4} t_{i,H'}$ | 0.064 | 0.067 | 0.080 | 0.107 | 0.110 |
| $\frac{F_{2,0}+F_{4,0}}{F_{1,0}+F_{3,0}}$ | −0.21 | −0.23 | −0.19 | −0.13 | −0.16 |
| $\frac{F_{3,0}}{F_{1,0}}$ | 0.81 | 1.20 | 1.39 | 0.82 | 0.75 |

TABLE V

Summary of the results of quadrant-hold analysis for water vapour flux of the five-runs in Table III

| $z/h$ | 0.12 | 0.42 | 0.60 | 1.00 | 1.38 |
|---|---|---|---|---|---|
| $H'$ | 17.4 | 8.2 | 34.6 | 5.0 | 5.2 |
| $\sum_{i=1}^{4} t_{i,H'}$ | 0.047 | 0.050 | 0.009 | 0.102 | 0.01 |
| $\frac{F_{2,0}+F_{4,0}}{F_{1,0}+F_{3,0}}$ | −0.67 | −0.37 | −0.71 | −0.30 | −0.30 |
| $\frac{F_{3,0}}{F_{1,0}}$ | 0.87 | 1.15 | 1.50 | 1.09 | 1.03 |

$$\left|\sum_{i=1}^{4} F_{i,H'}\right| = 0.5\,,$$

and $\Sigma_{i=1}^{4} t_{i,H'}$ is the corresponding time fraction. $H'$ and $\Sigma_{i=1}^{4} t_{i,H'}$ are measures of intermittency. The intermittent nature of the turbulent transport is obvious at all levels. Half the sensible heat flux was accounted for by events with a hole size larger than 5.7–3.5, which occupied a small fraction of time (6–11%), while for water vapour flux the values of $H'$ and $\Sigma_{i=1}^{4} t_{i,H'}$ were 34.6–5.2 and 1–10%, respectively.

The relative importance of the kinds of turbulent motion in the transport of scalars can be examined by calculating the ratios of the flux fractions at zero hole size. The variation of the ratio, $F_{3,0}/F_{1,0}$ with height was related to the source distributions. For sensible heat flux, it had values less than one at the tree tops ($z/h = 1.00$) and above the stand ($z/h = 1.38$), indicating that the warm updraft contribution to sensible heat flux exceeded the cool downdraft contribution. The cool downdraft contribution exceeded the warm updraft contribution in the middle and at the base of the canopy ($z/h = 0.60$ and 0.42), with the ratio $F_{3,0}/F_{1,0}$ greater than one. Close to the ground, at $z/h = 0.12$, the warm updraft contribution again exceeded the cool downdraft contribution. For water vapour flux, the moist updraft

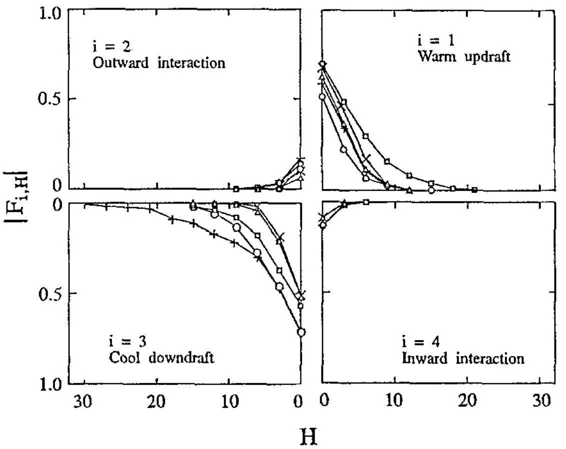


Fig. 11. Flux fraction $F_{i,H}$ plotted against hole size $H$ for sensible heat flux at $z/h = 1.38$ (×), 1.00 (△), 0.60 (○), 0.42 (+), and 0.12 (□).

and dry downdraft contributions were of about equal magnitude at $z/h = 1.38$ and 1.00. At $z/h = 0.60$ and 0.42, the dry downdraft contribution was greater than the moist updraft contribution, but the moist updraft contribution exceeded the dry downdraft contribution at $z/h = 0.12$.

The ratio of the contribution of the interactions to that of the cool (or dry) downdrafts/warm (or moist) updrafts, $(F_{2,0} + F_{4,0})/(F_{1,0} + F_{3,0})$, varied between $-0.23$ and $-0.13$ for sensible heat flux and between $-0.67$ and $-0.30$ for water vapour flux (Tables IV and V). In I, it was shown that the magnitude of this ratio for momentum flux exceeded one at $z/h = 0.42$ and 0.12. This was not the case for sensible heat and water vapour fluxes. At $z/h = 0.42$, where the air temperature inversion occurred, the magnitude of the ratio was smaller than one (0.23). This indicates that the transport of sensible heat at this height was of large scale and was no longer driven by the local temperature gradient.

Figure 11 shows the sensible heat flux fraction at different heights plotted against hole size. Unlike the case for momentum flux, there was very little contribution from the interactions beyond $H = 6$. For example, $(F_{2,6} + F_{4,6})/(F_{1,6} + F_{3,6})$, the ratio of the contribution of the interactions to that of the cool downdrafts/warm updrafts at $H = 6$, was $-0.003$ at $z/h = 0.60$ for sensible heat flux, while the corresponding ratio for momentum flux was much more negative, with a value of $-0.124$ (I). This difference, together with the difference in the magnitude of the ratio, $(F_{2,0} + F_{4,0})/(F_{1,0} + F_{3,0})$, indicates that the transfers of momentum and sensible heat are dissimilar due to different mechanisms and source distributions.

These results agree broadly with the observations made in other experimental studies in and immediately above vegetation canopies (Coppin *et al.*, 1986; Gao *et al.*, 1989; Maitani and Shaw, 1990; Bergstrom and Högström, 1989), with some differences in the fine details. For example, the cool downdraft-dominated region for sensible heat flux for the stand in the present study was confined below the tree tops, while that for a mixed deciduous forest reached as high as $z/h = 1.9$ (Maitani and Shaw, 1990).

## 4. Summary and Conclusions

The daytime eddy fluxes of sensible heat and water vapour within and above a Douglas-fir stand under low soil water conditions have been analyzed. The sum of sensible and latent heat fluxes above the stand accounted for, on average, 83% of the available energy flux. On some days, energy budget closure was far better than on others. The occurrence of a large energy imbalance on several occasions is believed to be associated with the possible non-zero value of the average vertical velocity measured at a single point.

The sum of sensible and latent heat fluxes beneath the overstory accounted for 74% of the available energy flux. One of the reasons for the energy imbalance was that the small number of soil heat flux plates and the short pathway of the radiometer tram system was unable to account for the large horizontal heterogeneity in the available energy flux beneath the overstory. The eddy flux of sensible heat, on the other hand, exhibited very little horizontal variation. Good agreement was obtained among the measurements of sensible heat flux made at $z/h = 0.12$ at four positions 15 m apart.

Sensible heat flux was the main output component of the energy budget both above and beneath the overstory. The average Bowen ratio had a value of 2.1 above the stand and 1.4 beneath the overstory. The mid-morning value of the canopy resistance was 150–450 s/m during the experiment and the mid-day value of the Omega factor was about 0.20. The daytime mean canopy resistance showed a strong dependence on the mean saturation deficit during the two-week experimental period.

The eddy flux profiles reflect source distributions. There was a constant flux layer in the trunk space, a large flux divergence in the canopy layer, and a constant flux layer above the stand. Counter-gradient flux of sensible heat constantly occurred at the base of the canopy ($z/h = 0.42$).

The transfer of sensible heat and water vapour was dominated by intermittent cool (or dry) downdraft and warm (or moist) updraft events at all levels. The ratio of the cool (or dry) downdraft contribution to the warm (or moist) updraft contribution was influenced to a large degree by the source distributions. For sensible heat flux, the ratio was greater than one in the canopy layer and less than one above the stand and near the forest floor.

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